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Technical Report

Interface and properties of the friction stir welded joints of titanium alloy Ti6Al4V with aluminum alloy 6061

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ABSTRACT

Titanium alloy Ti6Al4V and aluminum alloy 6061 dissimilar material joints were made with friction stir welding (FSW) method. The effects of welding parameters, including the stir pin position, the rotating rate and the travel speed of the tool, on the interface and the properties of the joints were investigated. The macrostructure of the joints and the fracture surfaces of the tensile test were observed with optical microscope and scanning electron microscope (SEM). The interface reaction layer was investigated with transmission electron microscopy (TEM). The factors affecting the mechanical properties of the joints were discussed. The results indicated that the tensile strength of the joints and the fracture location are mainly dependent on the rotating rate, and the interface and intermetallic compound (IMC) layer are the governing factor. There is a continuous 100 nm thick $TiAl_3$ IMC at the interface when the rotating rate is 750 rpm. When the welding parameters were appropriate, the joints fractured in the thermo-mechanically affected zone (TMAZ) and the heat affected zone (HAZ) of the aluminum alloy and the strength of the joints could reach 215 MPa, 68% of the aluminum base material strength, as well as the joint could endure large plastic deformation.

1. Introduction

Joining of titanium and aluminum alloys dissimilar materials has potential application in aerospace and automobile industry, which could reduce weight and cost (due to aluminum alloy) and improve strength, corrosion resistance and high temperature property (due to titanium alloy) of the structures. For example, the passenger seat track after AIRBUS conceptual design was manufactured with Ti6Al4V crown and aluminum alloy web by laser beam welding [1]. However, successful welding of titanium with aluminum alloys is of challenge, because there are many differences between the two alloys in physical, chemical and metallurgical properties. One of the key problems is the formation of brittle intermetallic compounds (IMCs) in Ti/Al joints [2].

In recent years, laser welding [1,3–5], diffusion welding [6–10], friction welding [11–13] and friction stir welding (FSW) [14–20] have been attempted to join the Ti/Al dissimilar alloys. Laser welding is a promising process for joining of dissimilar metals due to its high energy density, narrow fusion zone, rapid cooling speed and consequently the limited formation of IMCs. However it is still difficult to control the formation of Ti–Al compounds at the joint interface. It may deteriorate the mechanical properties of laser beam joints of Ti/Al dissimilar alloys [1,3]. Yao [6,7] reported on vacuum diffusion welding between titanium alloys and aluminum alloys. $TiAl_3$ intermetallic compounds was formed in the diffusion bonding of pure Ti/pure Al, while $Al_{18}Ti_2Mg_3$ was the unique product from the diffusion bonding of TA2/5A06. Friction welding could join dissimilar rods of titanium alloys and aluminum alloys and obtain high joint efficiency. When $Ti_2Mg_3Al_{18}$ intermetallic compound was formed in the joint interface, the joints fractured at the welded interface [11].

FSW, a solid-state joining technology, is also a potential choice for joining different alloys. Chen and Nakata [14] reported on friction stir lap welding between pure titanium and aluminum alloy, and the new phase of $TiAl_3$ formed at the joint interface by

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Al–Ti diffusion reaction. Dressler [16] reported that titanium alloy Ti6Al4V and aluminum alloy AA2024-T3 could be successfully butt joined by FSW. Since IMCs were not observed at the most part of the interface, the principal bonding mechanism of the interface was assumed to be the diffusion of atoms. Bang [17] researched the FSW of AA6061-T6 with Ti6Al4V dissimilar alloys of 5 mm thickness using a unique shaped tool with a circular truncated cone of the probe, but the ultimate tensile strength of the joint was just 134 MPa, approximately 35% of the aluminum alloy base metal tensile strength. The reason for the low strength of weld joint was supposed to be the insufficient stirring in the bottom zone of the Ti/Al interface. The joint interface revealed very complicate morphology including lamellar structure of Al alternating with Ti. IMCs were neither observed at the joint interface, similar to the result reported by Dressler [16]. Aonuma [18] investigated the butt joining of titanium alloy to aluminum alloy via FSW, and the joints mainly fractured in the mixed region of titanium alloy and aluminum alloy at the joint interface, $TiAl_3$ was found on the fractured surface. Chen [19] researched the FSW joint of Al/Ti dissimilar alloys, where zinc was added as the middle layer material. The joint became more brittle, because $TiAl_3$ and $Zn_{0.69}Ti_{0.31}$ intermetallic compounds were detected in the center region.

Although there are a few studies about friction stir butt welding of Ti/Al dissimilar alloys as mentioned above, the influence of welding parameters on the joint formation and the joint strength has not been studied. In the present study, the titanium alloy Ti6Al4V and aluminum alloy A6061, which are widely used in industries, are butt-welded with FSW. The effects of the main welding parameters, including the probe offset, the rotating rate and traveling speed of the tool, on the interface and the mechanical properties of the joints are investigated. The factors affecting the mechanical properties of the joints are discussed.

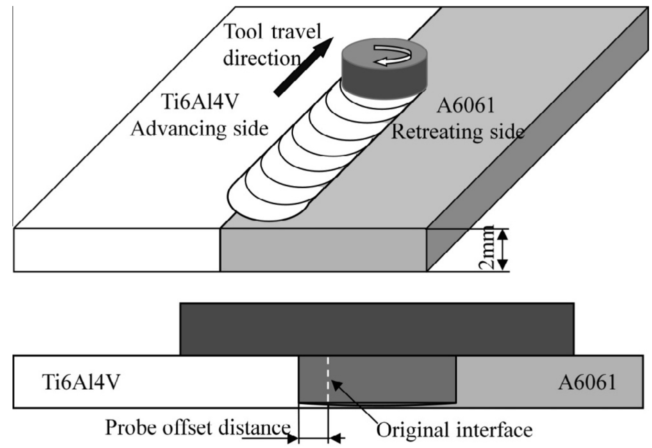

Fig. 1. Schematic illustration of friction stir butt welding of Ti6Al4V/A6061.

Table 2
Parameters for butt-welding of Ti6Al4V with A6061.

Tool material		WC–Co
Tool geometry	Shoulder diameter (mm)	15
	Probe diameter (mm)	6
	Probe length (mm)	1.9
Axial tool force (kN)		7.5
Tool rotating rate (rpm)		500, 750, 1000, 1250
Welding speed (mm/min)		120, 160, 200, 280
Tilt angle (degree)		3
Probe edge offset into the Ti alloy (mm)		0, 0.3, 0.6, 0.9, 1.2

2. Experimental details

Ti6Al4V and A6061-T6 plates with dimensions of 150 mm × 75 mm × 2 mm were used in the present study. The chemical compositions and mechanical properties of the two alloys are shown in Table 1. Friction stir butt welding of titanium alloy with aluminum alloy was conducted by offsetting probe edge into the titanium alloy, as illustrated by Fig. 1. The titanium alloy was positioned on the advancing side and the aluminum alloy was on the retreating side. The welding tool of FSW was made of a WC–Co based alloy and consisted of a concave shoulder of 15 mm diameter and a cylinder probe of 1.9 mm length and 6 mm diameter. The probe offset distance was selected to be 0–1.2 mm in the present study. Therefore, the stirring action of the probe mainly happened in the aluminum alloy part of the joint. The detailed welding parameters are given in Table 2. Before welding, the joint surface of the titanium and aluminum alloys was machined by a milling machine and degreased with acetone.

After welding, the joints were cross-sectioned perpendicularly to the welding direction for defect examination and metallographic analysis. The microstructures of joints were observed by optical microscope (OM) and scanning electron microscope (SEM, JEOL: JSM-6500F) equipped with an energy-dispersive X-ray spectrometer (EDS). The specimens for OM were etched with Keller's etchant (1.0 ml HF + 1.5 ml HCl + 2.5 ml HNO_3 + 95 ml H_2O) according to ISO/TR 16060:2003 [21]. Transmission electron microscopy (TEM) was used to analyze the IMCs at the joint interface.

Tensile specimens were cross-sectioned perpendicular to the welding direction. The strength of the joint was evaluated via tensile test at room temperature according to ISO 6892:1998 [22]. The tensile test was carried out using a testing machine INSTRON 5500 at a crosshead speed of 0.1 mm/min. Three specimens were tested for each welding bead, and the average value was used to evaluate the tensile strength of the joint. The dimension of the tensile specimen was 100 mm × 10 mm × 2 mm with the surfaces of no machining. Fracture surfaces of joints were analyzed using SEM–EDS and X-ray diffraction (XRD) after the tensile test.

3. Result and discussion

3.1. Effects of welding parameters on the joint formation

Within the welding conditions shown in Table 2, the welding parameters with which the acceptable joints could be formed are shown in Fig. 2. When the offset is zero, no acceptable joint could be formed. Small offset needs higher rotating rate and lower welding speed. When the offset is 0.9 mm and 1.2 mm, wider (broad) ranges of the rotating rate (500–1000 rpm) and welding speed (120–280 mm/min) are suitable to form acceptable joints.

Table 1
Chemical compositions and mechanical properties of the base materials (wt.%).

Alloys	Ti	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	V	C	O	N	H	Tensile strength σ_b (MPa)	Yield stress $\sigma_{0.2}$ (MPa)	Elongation (%)
A6061P-T6	0.02	Bal.	0.63	0.29	0.27	0.07	1.00	0.17	0.01	–	–	–	–	–	318	289	11.2
Ti6Al4V	Bal.	6.21	–	0.135	–	–	–	–	–	3.93	0.023	0.126	0.003	0.002	952	877	12.6

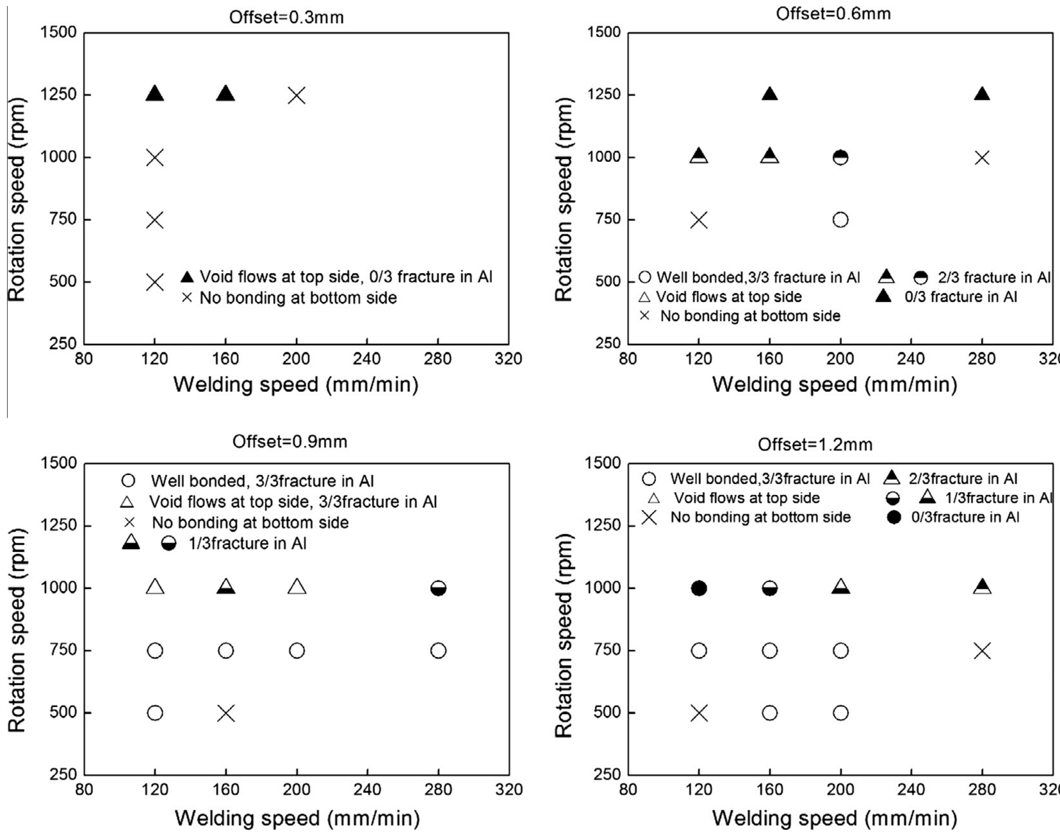

Fig. 2. Welding parameters for sound joints with different probe offset distance, (a) 0.3 mm, (b) 0.6 mm, (c) 0.9 mm and (d) 1.2 mm.

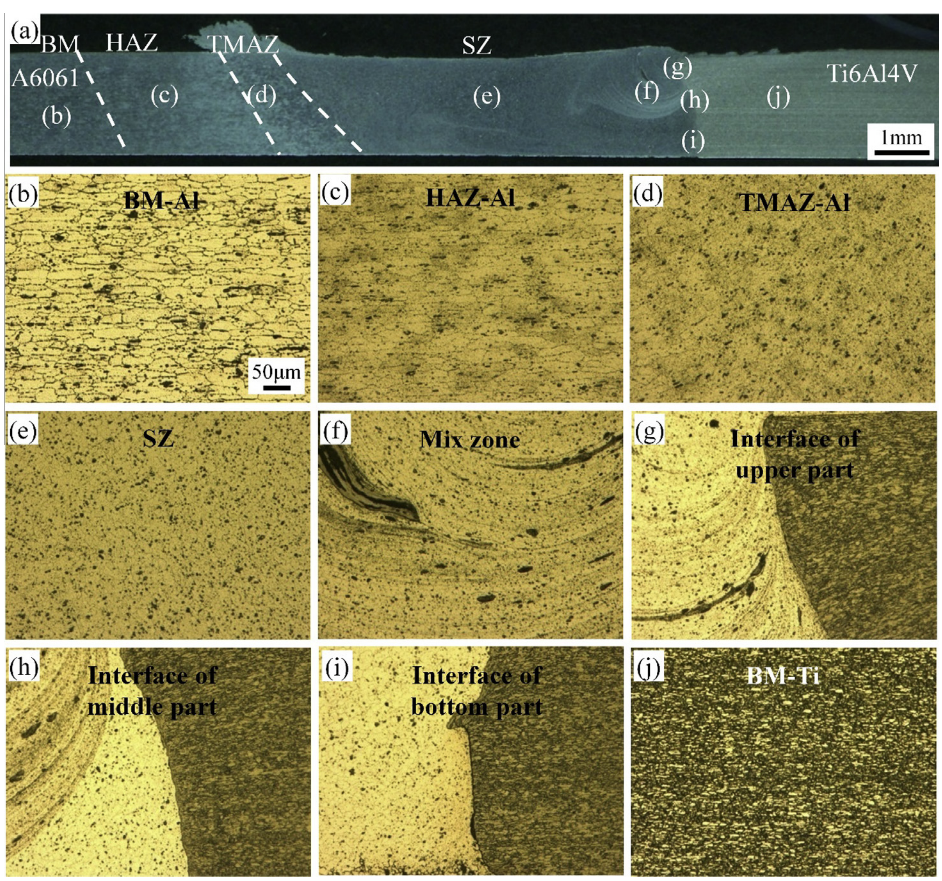

Fig. 3. Typical microstructure of the joint (750 rpm – 200 mm/min – 1.2 mm).

Higher rotating rate (1250 rpm) should be combined with small offset (0.3 mm and 0.6 mm) for sound joint formation.

As for the FSW of the dissimilar materials of Al alloy A6061-T6 with Ti alloy Ti6Al4V, since the proper welding parameters of Ti alloy and Al alloy are different due to their different properties (for example, A6061-T6 was prone to be bonded with higher rotating rate and higher welding speed, while Ti6Al4V was necessarily welded with lower rotating rate and lower welding speed), it is difficult to acquire defect free joints with the plunging of the probe in the center of the butt joint. The probe was generally inserted mainly on the aluminum alloy side and the probe edge was slightly offset into the titanium alloy. The stirring action of the probe mainly happened in the aluminum alloy part of the joint. The welding parameters tend to be close to those of Al alloy. The lower rotating rate and higher welding speed would produce the wormhole defect in the stir zone of the Al alloy. In the case of more offset distance, the more Ti6Al4V materials were stirred and suffered the action of the shoulder, so that the higher welding speed and rotating rate would lead to the defects in the Ti alloy. In the case of smaller offset distance, lower rotating rate and higher welding speed, the plastic flow of the materials around the interface was more inadequate, especially at the bottom. It produced no bonded defect at the interface of the bottom.

3.2. Typical microstructure of the joint

The typical microstructure of the joint is shown in Fig. 3. The joint consisted of the base material/the heat affected zone (HAZ)/the thermo-mechanically affected zone (TMAZ) of Al alloy side, the stirred zone (SZ) of Al alloy, the mix zone of Al alloy with Ti alloy particles, the interface, and the TMAZ/HAZ/base material of Ti alloy side. The map of EDS element distribution at the center of the stir zone indicated that no Ti alloy particles stirred into this zone. The mix zone near the interface consisted of Al alloy fine grains and a little Ti alloy particles or fragments.

The back-scattered electron images of interfacial microstructure of joints at the different position along the thickness are shown in Fig. 4. There is no great difference in the interfacial microstructure along the thickness.

Investigation on the interface with TEM showed that there exists a continuous $TiAl_3$ IMC layer of about 100 nm thickness at the interface (Fig. 5). It means that with the FSW conditions used in this paper the Ti element and Al element at the interface could react to form $TiAl_3$ IMC. Aonuma's work [18] considered that a Ti–Al intermetallic compound of $TiAl_3$ forms mainly at the interface of the Ti alloys and Al alloys at the FSW joints. Compared with Aonuma's work, this work confirms that no other phases exists except $TiAl_3$ at the interface by TEM.

3.3. Tensile strength of the joints and the fracture location

The tensile strength of the joints bonded with various parameters and the fracture location were shown in Fig. 6. The rotating rate is the key factor affecting the tensile strength and the fracture location.

The joints bonded with the rotating rate of 750 rpm all failed at the TMAZ/HAZ of the Al alloy side, and the strength was relatively higher. The highest tensile strength reached 215 MPa, 68% of the Al

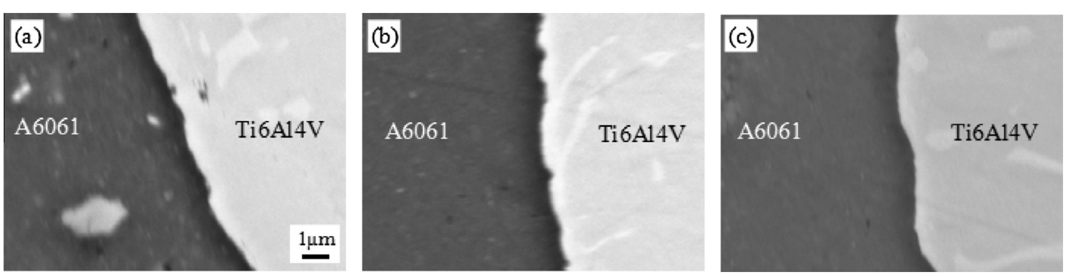

Fig. 4. Back-scattered electron images of interfacial microstructure of joints at 750 rpm – 120 mm/min – 0.9 mm offset: (a) top zone, (b) middle zone and (c) bottom zone.

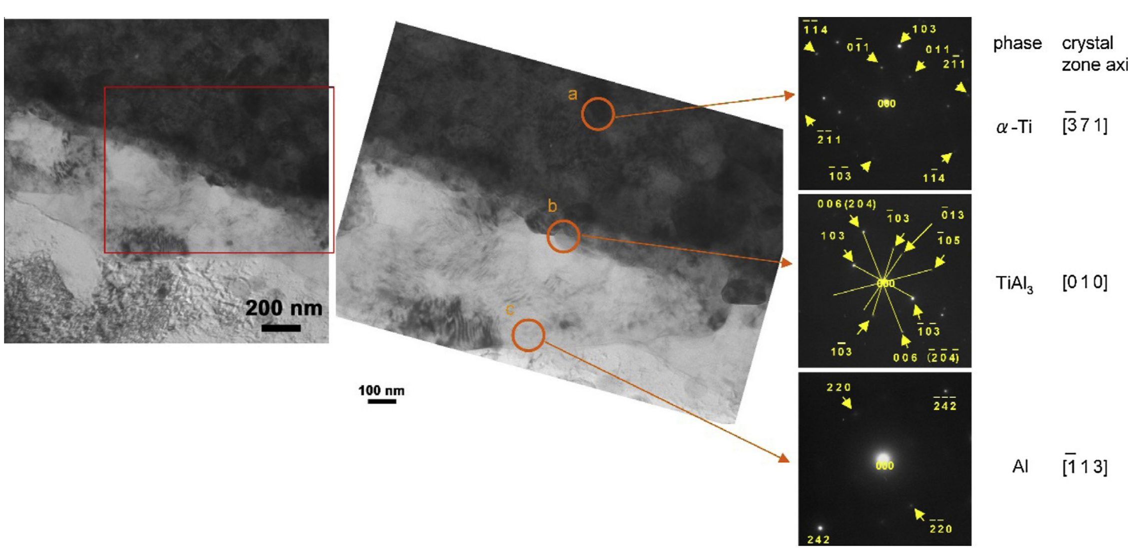

Fig. 5. TEM of the joint interface at middle part and the diffraction patterns of the various areas (750 rpm – 160 mm/min – 1.2 mm).

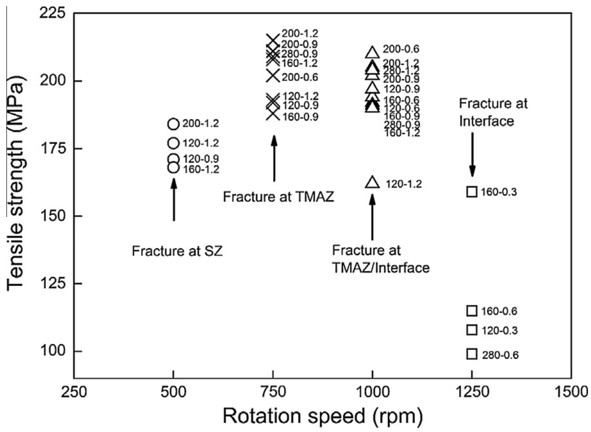

Fig. 6. Effects of the welding parameters on the tensile strength of the joints and the fracture location.

alloy base material's strength. The curve (Fig. 7a) of the load with displacement shows that the joint could endure plastic deformation.

The joints bonded with the rotating rate of 1250 rpm all failed at the interface of the Ti alloy and Al alloy, and the strength was the lowest, just 31–50% of the Al alloy base material's strength. The curve (Fig. 7b) of the load with displacement shows its brittle fracture characteristics.

The joints bonded with the rotating rate of 500 rpm all fractured in the stir zone of the Al alloy, and the strength was within 168–184 MPa, 53–58% of the Al alloy base material's strength. The plastic fracturing behavior is presented in the tensile curve (Fig. 7c).

For the joints bonded with the rotating rate of 1000 rpm, some of them fractured at the TMAZ/HAZ of the Al alloy side, but others fractured at the interface of the Ti alloy and Al alloy. As the offset distance was large, the lower welding speed would lead to fracture at the interface of the Ti alloy and Al alloy. The tensile strength of the joints bonded with the rotating rate of 1000 rpm was higher than those of the joints bonded with the rotating rate of 500 rpm and 1250 rpm, except the one fractured at the interface with 1000 rpm – 120 mm/min – 1.2 mm welding parameters. The joints fractured at the TMAZ/HAZ of the Al alloy side showed plastic rupture, while the joints fractured at the interface appeared brittle characteristics.

3.4. Effects of rotating rate on the interfacial microstructure and the joint strength

The results of the joint tensile tests indicated that the fracture location was mainly dependent on the rotating rate. When the rotating rate was 1250 rpm, the joints all failed at the interface. The microstructure of interface shows the thicker mix and reaction layers (Fig. 8a), and the test on the fractured surface with XRD implies the existence of $TiAl_3$ reactive production (Fig. 8b). It is deduced that the joint fractured at the interface associated with the thicker mix and reaction layers. The higher rotating rate of 1250 rpm would induce thick interface, resulting in fracturing at the interface and having the lowest tensile strength of the joint.

For the joints welded with the rotating rate of 500 rpm, the microstructure at the interface is shown in Fig. 9. At this rotating rate, the interface was well bonded accompanied with the thin interfacial layer. The joints all failed in the stir zone of Al alloy. The fractured surface with SEM shows the insufficient extruding characteristics (Fig. 10).

When the rotating rate was 750 rpm, the joints all failed at TMAZ/HAZ of Al alloy. No obvious thick mix and reaction layer was found on the microstructure at the interface, and no defect was inspected at the interface (Fig. 11). It implies that the interface was bonded soundly, and it was stronger than the TMAZ/HAZ, thus the joint failed at the TMAZ/HAZ.

When the rotating rate is 1000 rpm with lower welding speed of 120 mm/min and large offset of 1.2 mm, the interface of the

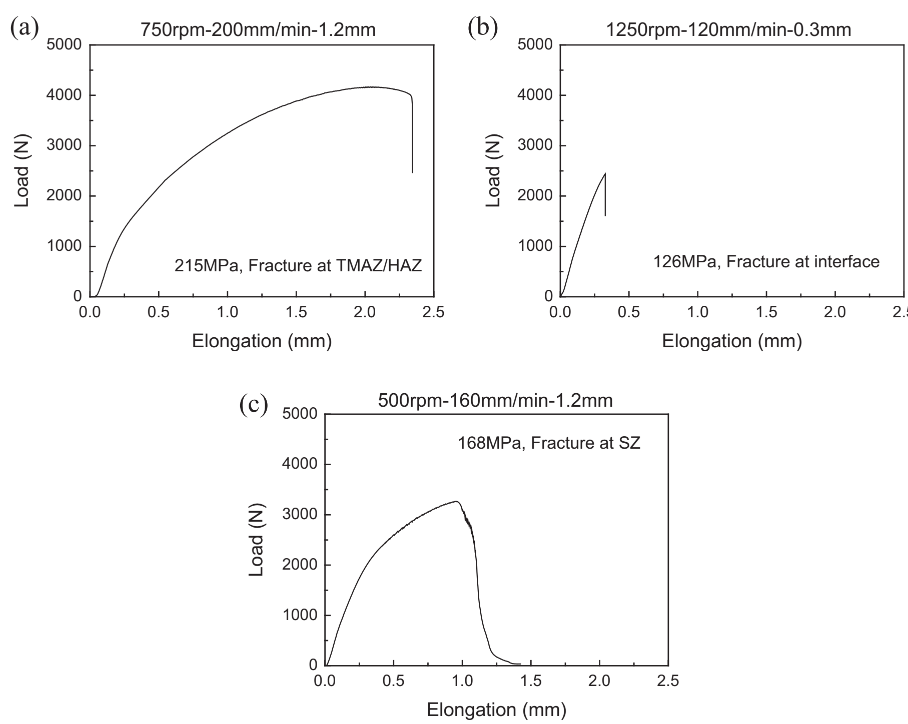

Fig. 7. Tensile curves with three fracturing locations: (a) at TMAZ/HAZ of Al alloy, (b) at the interface and (c) in the stir zone.

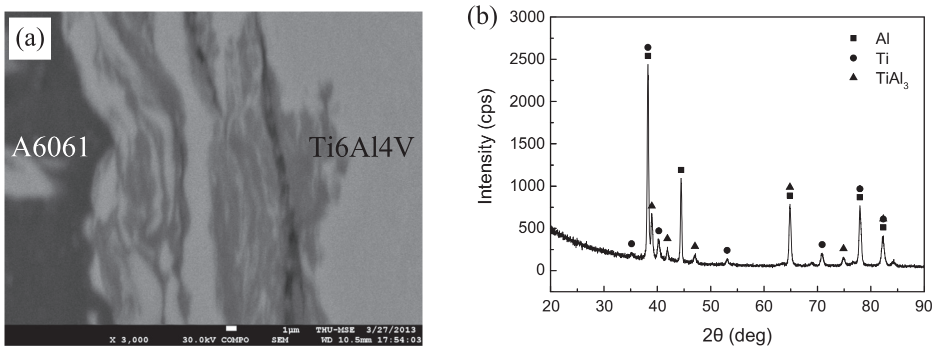

Fig. 8. Microstructure at the interface (a) and the XRD result of the fractured surface of Al side (b) of the joint with 1250 rpm – 160 mm/min – 0.6 mm offset.

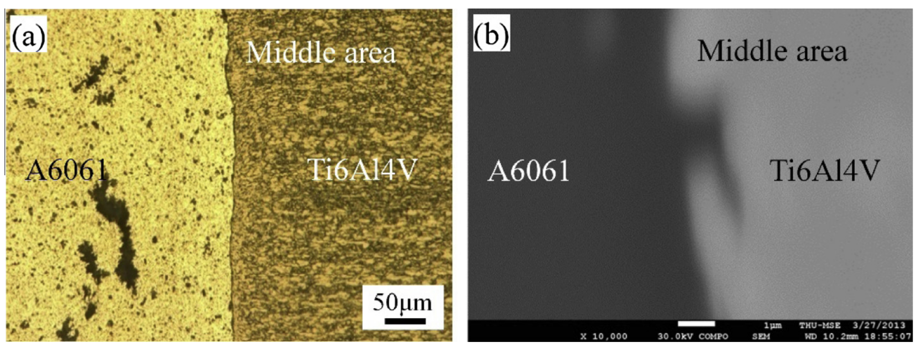

Fig. 9. Microstructure at the interface of the joint with 500 rpm rotating rate with optics (a) and SEM (b) (500 rpm – 160 mm/min – 1.2 mm).

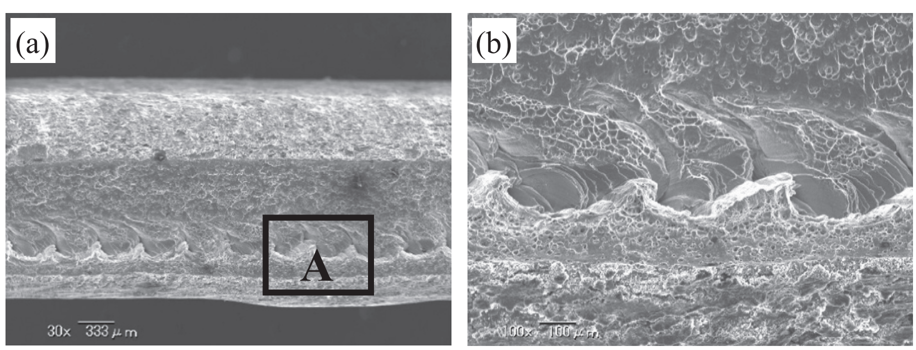

Fig. 10. Fractured surface of the joint failed in the stir zone (SEM): (a) fractured surface and (b) A zone (500 rpm – 160 mm/min – 1.2 mm).

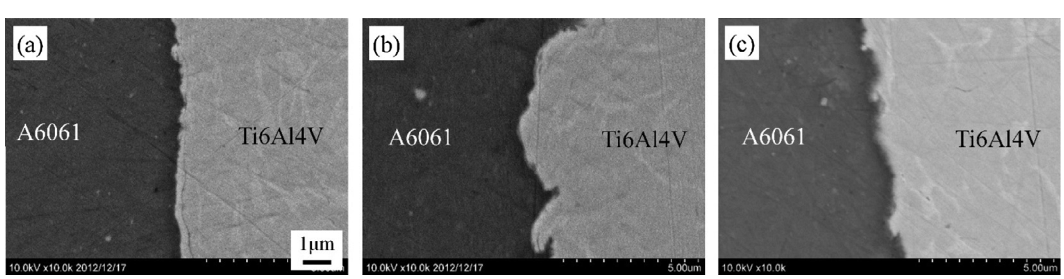

Fig. 11. Microstructure of the interface in the middle of the joint with 750 rpm at various welding speed and offset: (a) 750 rpm – 200 mm/min – 1.2 mm, (b) 750 rpm – 120 mm/min – 1.2 mm and (c) 750 rpm – 280 mm/min – 0.9 mm.

joint was thick. The joint fractured at the interface, and on the fractured surface IMCs could be found (Fig. 12). The microcracks existed in the IMC layers, leading to brittle fracture along the joint interface. Some aluminum alloy was also observed on the titanium alloy side, and the fracture of this part was dimple fracture. At the same rotating rate of 1000 rpm, while the welding speed is higher

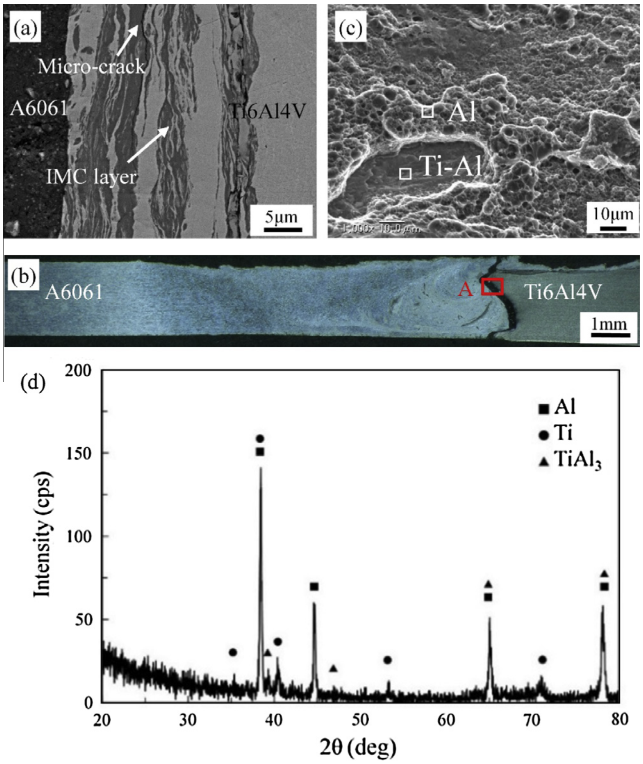

Fig. 12. Interface (a), fracture location (b), fractured surface (c), and XRD of the fracture surface of Ti side (d) of the joint with 1000 rpm – 120 mm/min – 1.2 mm.

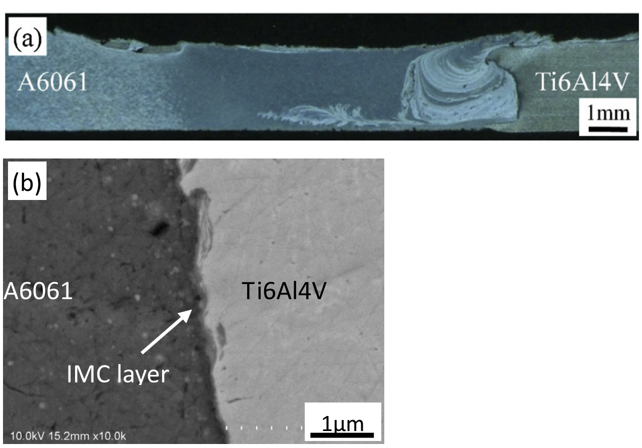

Fig. 13. Microstructure of the joint (a), and the interface in the middle (b) with 1000 rpm – 200 mm/min – 0.9 mm.

(200 mm/min) and the offset is small (0.9 mm), the joint fractured in the TMAZ of Al alloy. The microstructure at the interface is shown in Fig. 13. The interface and the IMCs layer are not thick. If the joint was bonded with the same rotating rate of 1000 rpm, welding speed of 160 mm/min and offset of 1.2 mm, the interface was thicker than that with 200 mm/min and 0.9 mm, but thinner than that with 120 mm/min and 1.2 mm (Fig. 14). Among three tensile specimens, one specimen fractured in the TMAZ of Al alloy, and the other two specimens fractured at the interface.

Summarizing above results, it could be concluded that the strength of the joint and the fracture location are mainly dependent on the interface thickness. If the interface is thick, the joint fractured at the interface and the strength of the joint is low. If the interface is well bonded and thin, the joint fractured in the TMAZ or the SZ of Al alloy, and the strength of the joint is relatively higher than those of the joints fractured at the interface. Within the three welding parameters (rotating rate, welding speed and offset), the rotating rate is the most important parameter affecting the interface bonded. Higher rotating rate (1250 rpm) leads thicker interface and lower strength of the joint.

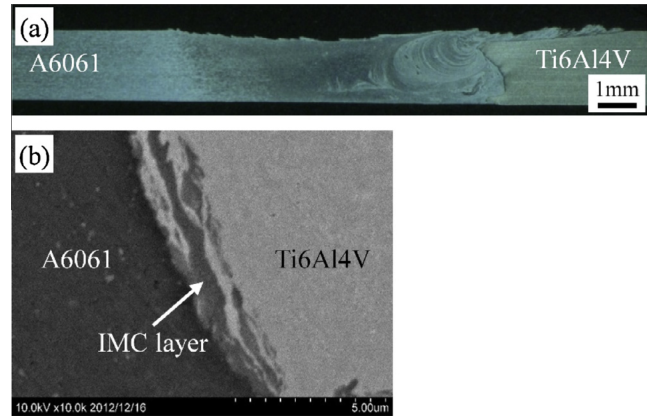

Fig. 14. Microstructure of the joint (a) and the interface in the middle (b) with 1000 rpm – 160 mm/min – 1.2 mm.

Compared with Refs. [16–18], the influence of welding parameters on the interface and the tensile strength of the joint is systematically researched in the paper. The relationship of the welding parameters, the interface and the strength of the joint is also discussed. The paper first proposes that rotating rate is the most important parameter affecting the interface bonded.

4. Conclusions

There exists continuous $TiAl_3$ IMCs layer at the interface of the Ti6Al4V/6061 FSW joint with the welding parameters used in this paper. The tensile strength and the fracture location were mainly dependent on the interface thickness, which is associated with the rotating rate. The joints bonded with 1250 rpm fractured at the interface had the lowest strength, associated with the thicker interface layers. The joints bonded with 500 rpm failed in the stir zone had lower strength, due to insufficient extruding. The joints bonded with 750 rpm failed in the TMAZ/HAZ had the highest strength, accompanied with the perfect bonded and thin interface. The strength of the joints could reach 215 MPa, 68% of the aluminum base material strength, as well as the joint could endure large plastic deformation.

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